High Temperature Superconducting Inductor
for Antenna Matching

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Abstract

There is an Army need to improve the sensitivity of its radio frequency receivers. Towards this goal, the U.S. Army Research Laboratory is developing a high critical temperature superconducting spiral inductor and cryogenically cooled amplifier to demonstrate increased sensitivity. The capacitive antenna is impedance matched to the signal processing network via a superconducting spiral inductor that provides the lowest possible loss and best signal-to-noise ratio, thus allowing detection of weaker signals.

Introduction

Thin films of high critical temperature superconductors (HTSCs) have been used for a variety of devices [1–7] since the discovery of this class of materials in 1986 by Bednorz and Müller [8]. However, because of the complexity of these materials, including processing issues and required cryogenic reliability, HTSCs have been slow to find specific device and systems applications. Due to the chemical composition, crystal structure, and anisotropic superconducting properties of HTSCs [1,2], stringent requirements are placed on the substrate used for thin film growth. To achieve the best superconducting properties, the substrate must be chemically compatible and have reasonably good matches in thermal expansion coefficient and lattice parameter with the HTSC [9]. For microwave device applications, the substrate also should be low loss, isotropic with respect to microwave radiation, and have a low dielectric constant. For most device applications, the HTSC is deposited with the c-axis normal to the substrate surface, since these fully oxygenated films possess the highest critical transition temperature (T_c), smallest critical transition temperature width (ΔT_c), and largest critical current density (J_c) [10].

Here, we report the use of minimal-resistive-loss HTSC inductors for impedance matching of inherently capacitive reactance short antennas to signal processing networks. Improving the signal-to-noise ratio at the receiving network can enhance system performance. With this aim, a cryocooled amplification system (at 77 K) is being fabricated and characterized.

Inductor Modeling

Two 25-turn and 35-turn rectangular spiral inductors with 25-μm widths and 25-μm spacings were modeled on $LaAlO_3$ at radio frequency (RF) by the use of "Sonnet Software," a full 3-D electromagnetic simulator. This software was developed to simulate multilayer planar structures and is almost ideal for this type of problem. The program works by gridding the desired structure into a large number of rectangular cells and solving the current distributions in those cells using the method of moments. Computation time increases geometrically with the number of cells, and therefore simulating much larger inductors is prohibitive. The height, dielectric constant, and loss tangent of the substrate and the conductivity of the conductors are used in "Sonnet" to accurately model dispersion, stray coupling, discontinuities, surface waves, moding, metallization loss, dielectric loss and radiation loss.

The actual physical parameters used to model the spiral inductors are a substrate height of 1000 μm, relative dielectric constant of 24, loss tangent of 0.0001, and a metal conductivity of 2.6×10^7 ohms/$\sqrt{Hz}$/sq. Each inductor was modeled as a one port with the other port shunted to ground using a via hole. The results from the simulations are shown in figures 1 and 2.
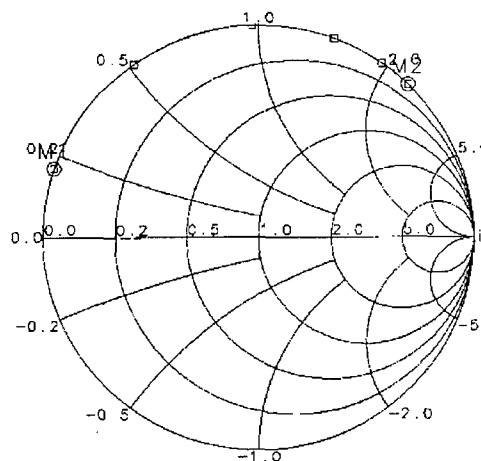

Figure 1. Computer simulation of a 25-turn rectangular HTSC coil generated with "Sonnet."
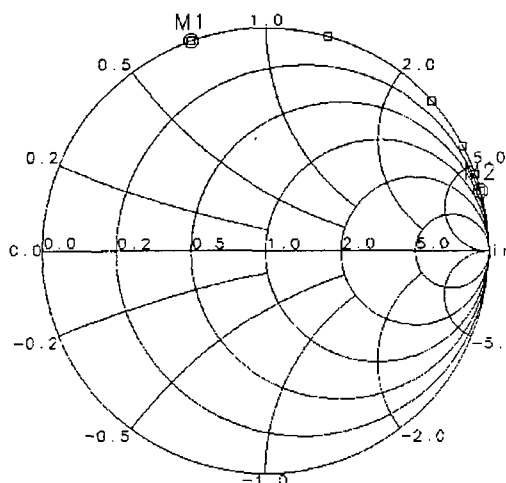
Figure 2. Computer simulation of a 35-turn rectangular HTSC coil generated with "Sonnet."

Figure 3. Superconducting transition temperature, T_c, of 88 K and transition width, ΔT_c, of less than 1 K of a YBCO film as measured using the ac eddy current technique [13].

Superconducting Film Preparation and Inductor Fabrication

Film Growth

High critical temperature superconducting films that are patterned to form the inductor were grown by the pulsed laser deposition technique [11,12]. The irradiation of a 90 to 98 percent dense bulk stoichiometric polycrystalline $Y_1Ba_2Cu_3O_{7-\delta}$ (YBCO) target at a laser fluence of 1 to 2 J/cm^2 using a KrF excimer laser ($\lambda = 248$ nm, 20-ns pulse duration), operating at 10 Hz for 10 minutes, provides 3000 Å of stoichiometric material at the substrate, which is in the on-axis configuration 7.0 cm from the target. High-quality superconducting films are obtained when the target material is deposited on 20-mil-thick, 1 cm × 1 cm, (001) oriented single-crystal $LaAlO_3$ substrates that are heated to about 900 °C in an oxygen partial pressure of about 100 mTorr. The substrates are silver pasted to an inconel block, which is backside heated with a quartz halogen lamp. An infrared pyrometer provides verification of the substrate temperature and the uniformity of temperature across the substrate surface. Once the film deposition is complete, the sample is cooled in 1/2 atmosphere of oxygen from 650 to 400 °C over 30 minutes to reach the oxygen stoichiometry required for superconductivity.

Film Characterization

The superconducting films are characterized by an ac eddy current technique [13] for verification of the super-conducting transition temperature and transition width. As measured by the ac eddy current technique, the data (fig. 3) show an HTSC film transition of $T_c = 88$ K with $\Delta T_c < 1$ K. All the as-grown films exhibit T_c's > 85 K and typically $\Delta T_c < 1$ K. Also, x-ray diffraction (XRD) is used to verify the crystal orientation and quality of the HTSC film.
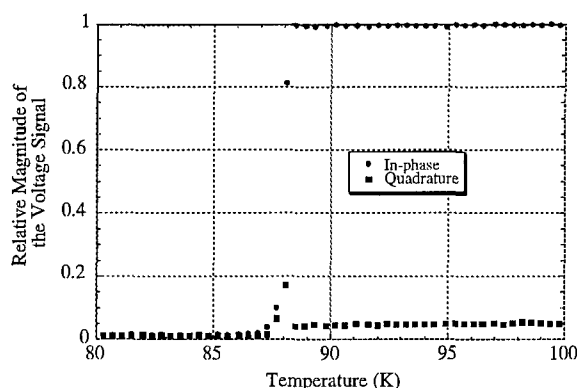
The crystallinity of a typical film grown for the inductor is demonstrated in figures 4 and 5. Figure 4 is a θ–2θ plot showing the c-axis orientation of the YBCO film with respect to the substrate surface. Due to the anisotropic nature of the HTSCs, c-axis oriented films are preferred for most device applications [10]. Figure 5 is the rocking curve for the (006) reflection region of YBCO; the narrowness of the rocking curve width, about 400 arc-seconds or 0.0.11°, indicates that the film is single-crystal–like. While the critical current density, J_c, and surface resistance, R_s, were not measured for these films, other films grown under similar deposition conditions at this laboratory, and having similar XRD and eddy current properties, typically exhibit J_c's of 10^6 to 10^7 A/cm^2 at 10 K and R_s lower than copper at 77 K and 35 GHz.

Device Patterning

Each bare YBCO film is coated with 1000 Å of SiN. The spiral is then patterned with photolithographic techniques. The SiN layer in the patterned region is reactive ion etched to expose the unwanted portion of the YBCO film, which is stripped with 0.5% nitric acid. The patterned spiral is coated with another 1000 Å of SiN. Electrical contact regions to the spiral are then patterned using photolithographic techniques. The SiN layer in the region where electrical contacts are made is removed by reactive ion etching to expose the YBCO film. Gold is then deposited on top of the structure to a thickness of 5000 Å. The contacts are then formed by the use of acetone to lift off the unwanted gold. The gold contacts are then alloyed to the YBCO layer by heating of the structure to about 500 °C in flowing oxygen for about 30 minutes. Finally, the top gold line that connects the center region of the inductor to the device is fabricated. This is accomplished by depositing 5000 Å of gold onto a photolithographically defined pattern and using acetone to lift off the excess gold.
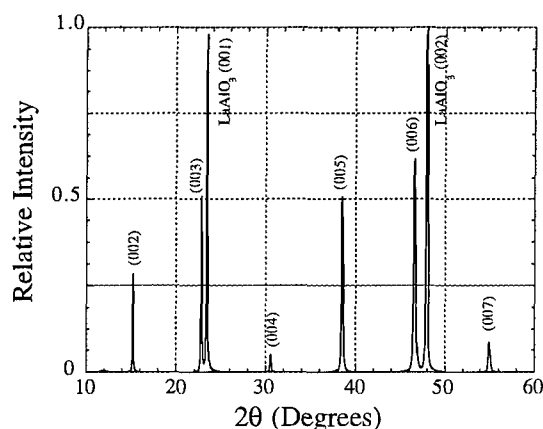
Figure 4. X-ray diffraction pattern showing the high crystalline quality c-axis orientation of the YBCO film on the (001) oriented single crystal LaAlO₃ substrate.
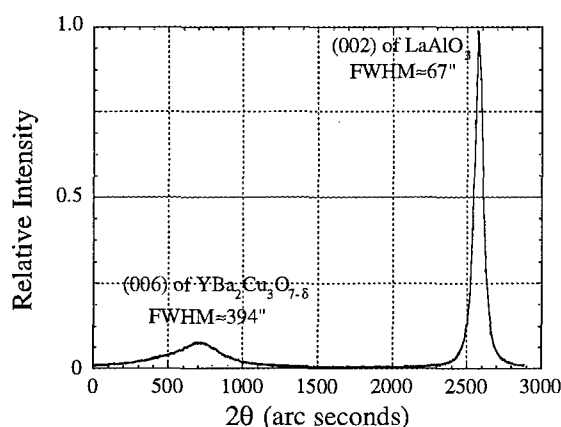

Figure 5. Two-crystal x-ray rocking curve spectrum of a YBCO film on an (001) oriented single crystal LaAlO₃ substrate. The 400 arc-second FWHM rocking curve width for the YBCO film indicates the single-crystal–like nature of the HTSC film.

Inductor Performance

Test results on a 70-turn gold spiral inductor are in agreement with the modeled data. The results (fig. 6) show that the inductor is actually capacitive at the tested frequencies. A 70-turn spiral inductor was never actually modeled due to the extensive computation time; however, if the modeled results from the 25- and 35-turn spirals are extrapolated to that of a 70-turn spiral, the modeled and measured results are in agreement.

Amplifier

A two-stage low-noise cryogenic amplifier was designed and fabricated with GaAs heterojunction bipolar transistors (HBTs). A significant amount of time was spent finding a transistor capable of operating simultaneously at liquid nitrogen temperature and at radio frequencies. The GaAs HBTs showed increased gain at cryogenic temperatures, while most silicon-based transistors failed to operate because of carrier freeze out. High-frequency GaAs-
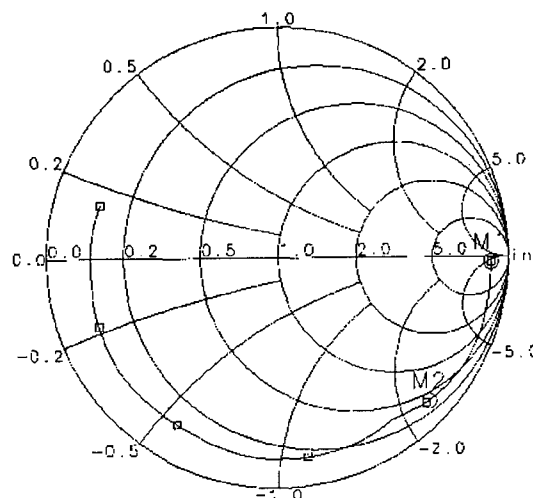

Figure 6. Measured performance of a 75-turn coil inductor fabricated of gold.

based metal semiconductor field effect transistors (MESFETs) and high-electron-mobility transistors (HEMPTs) were tested and worked well at cryogenic temperatures, but their excessive gain and high input impedances at these frequencies made them undesirable for this application.

The amplifier topology chosen was a first-stage common base followed by a capacitor-coupled common emitter. The first-stage common base configuration provides the easiest solution for matching to a low source impedance, in this case 18 ohms, due to its inherently low input impedance. At RF, the common-base HBT has negligible reactance; therefore, the device input impedance can be tuned to 18 ohms (fig. 7) by selection of the proper bias point. A common emitter configuration was used for the second stage. Since the common emitter input impedance is comparable to the output impedance of the first-stage common base, minimal interstage matching is required. The
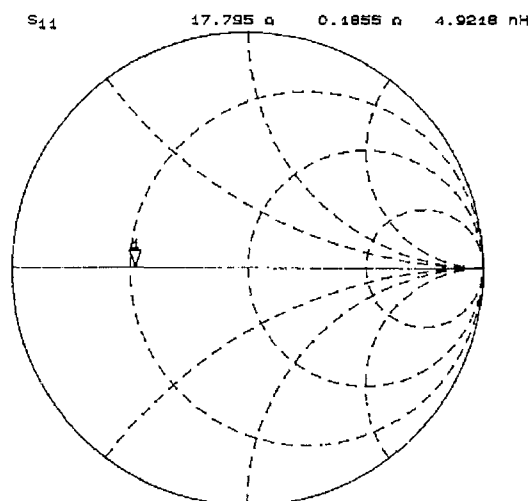

Figure 7. Proper selection of the bias point allows the cryogenically cooled common-base HBT to be tuned to 18 ohms at RF.

second-stage common emitter output impedance was matched to 50 ohms with a simple impedance transformer. An inductor-capacitor-inductor tee network will be investigated to provide a much better match in the future. However, with the initial chosen topology, sufficient gain of greater than 20 dB was achieved, as shown in figure 8.

Conclusions

A high-sensitivity RF cryogenic receiver has been developed to detect RF signals that previously were not detectable. The improved sensitivity can be attributed to reduced losses in the input matching network, a factor of 4 reduction in the thermal noise floor, and the improved performance of the GaAs HBTs at cryogenic temperatures. Combined, these improvements can increase receiver sensitivity by greater than 6 dB, significantly increasing the detection range.

Figure 8. The chosen amplifier topology provides sufficient gain: >20 dB.

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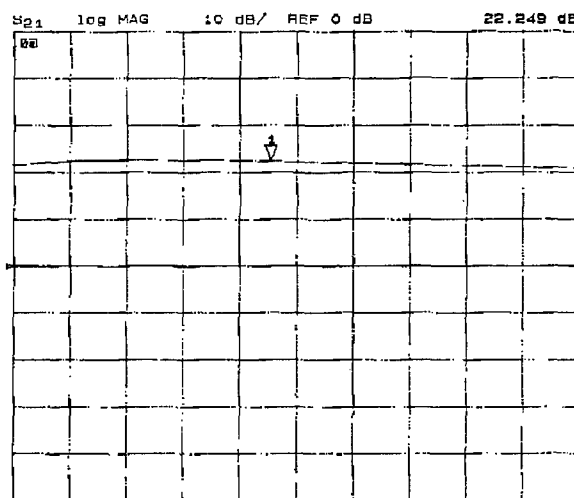13. J. D. Doss, D. W. Cooke, C. W. McCabe, and M. A. Maez, Rev. Sci. Instrum. **59**(4), 659 (1988).

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